PROGRESS IN FIRST-PRINCIPLES BOUNDARY SIMULATIONS OF PLASMA TURBULENCE AND NEUTRAL DYNAMICS WITH THE GBS CODE

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We present recent progress in the understanding of the physics mechanisms and predictive capabilities obtained with the GBS code. GBS [1] simulates self-consistently plasma turbulence and neutrals in the boundary of magnetic confinement devices in three-dimensions with no separation between fluctuating and equilibrium quantities. In its most general formulation, GBS evolves three charged species (electrons, D^+, D_2^+) and two neutral species (D and D_2), interacting through ionization, charge exchange, recombination, and molecular dissociation, which are subject to recycling phenomena at the wall. Plasma species are modelled with drift-reduced fluid Braginskii equations, while a kinetic model is used for the neutral dynamics. GBS flexible numerical algorithm allows simulations in arbitrary magnetic configurations, including complex wall geometries.

We first focus on the effect of triangularity on tokamak boundary turbulence [2]. The simulations show that negative triangularity stabilizes turbulence, and linear investigations reveal that this is due to a reduction of the magnetic curvature drive of the resistive ballooning mode. Consequently, the pressure decay length L_p, related to the scrape-off layer power fall-off length λ_q, is found to be affected by triangularity. Leveraging considerations on the effect of triangularity on the linear growth rate and nonlinear evolution of the resistive-ballooning modes, the analytical theory-based scaling law for L_p in L-mode plasmas, derived in Ref. [3], is extended to include the effect of triangularity. The scaling agrees with nonlinear simulations and a multi-machine experimental database, which includes recent TCV discharges dedicated to the study of the effect of triangularity in L-mode diverted discharges.

We then explore the physical mechanisms regulating the power sharing at the outer targets of L-mode double-null configurations [4]. Scans of parameters that regulate the turbulent level, such as the plasma resistivity and the magnetic imbalance, reveal that the power asymmetry in double-null configurations is determined by the combined effects of diamagnetic drift, turbulence, and geometrical factor. Leveraging these observations, an analytical theory-based scaling law for the power-sharing asymmetry is derived and compared with nonlinear simulations. These comparisons indicate that the scaling law effectively captures the trends observed in simulations. Validation with experimental data from TCV DN discharges demonstrates agreement of the scaling law with the experimental results.

In order to study the physics of detachment, simulations of high-density deuterium plasmas in a lower single-null magnetic configuration based on a TCV discharge are presented [5]. To control the divertor conditions, a gas puffing is used. The increase in fuelling leads to an increase of density in the scrape-off layer and a decrease of the plasma temperature. At the same time, the particle and heat fluxes to the divertor target decrease and the detachment of the inner target is observed with varying divertor leg length and constant power. As observed experimentally, a longer leg leads to detachment at lower upstream plasma density. The analysis of particle and transport balance in the divertor volume shows that the decrease of the particle flux is caused by a decrease of the local neutral ionization together with a decrease of the parallel velocity, caused by the lower plasma temperature and the increase in momentum losses. The relative importance of the different collision terms is assessed, showing the crucial role of molecular interactions, as they are responsible for increasing the atomic neutral density and temperature, since most of the neutrals are produced by molecular activated recombination and dissociation. The presence of strong electric fields in high-density plasmas is also shown, revealing the role of the **E × B** drift in setting the asymmetry between the divertor targets. Simulation results agree with experimental observations of increased density decay length, attributed to a decrease of parallel transport, together with an increase of plasma blob size and radial velocity.

By taking advantage of the numerical algorithm implemented in GBS, the first results of three-dimensional, flux-driven, electrostatic, global, two-fluid turbulence simulations of a diverted tokamak configuration with applied resonant magnetic perturbations generated by a set of saddle coils are presented [6]. The simulations of an L-mode plasma show that the heat flux pattern on the divertor targets is affected by the resonant magnetic perturbations, because of the interplay between turbulent cross field transport and parallel flows. The simulation results reveal the potential of resonant magnetic perturbations to reduce the heat flux to the wall. In fact, the peak of the toroidally-and time-averaged heat flux as well as its value integrated over the divertor decrease as the amplitude of the magnetic perturbation increases, while the plasma sources are held constant.

Finally, the geometrical operators appearing in the drift-reduced Braginskii equations evolved by GBS are expanded considering the typical parameter ordering of stellarator configurations [7]. Simulations of an island divertor stellarator show that, although the island magnetic field-lines divert the plasma towards the strike points of the walls, the islands do not seem to have a significant impact on the turbulence properties. The dominant mode, identified as interchange-driven, is field-aligned and breaks the stellarator toroidal symmetry. The radial and poloidal extensions of the mode are of the same order, in contrast to typical tokamak simulations. Turbulent stellarator simulations are then validated against TJ-K experimental results [8].

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